MODERN AND ANCIENT COAL BED FIRES IN THE POWDER RIVER BASIN [1]

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Abstract. Hundreds of coal bed fires burn today in the Powder River Basin of southeast Montana and northeast Wyoming. Some consume coal in abandoned underground mines or burn in highwalls and spoil piles at active surface mines. But they are only part of the picture. Natural coal fires caused by lightning strikes, range and forest fires, and spontaneous combustion have left a record of clinker on hilltops and ridges throughout the landscape. The reddish, brick- to lava-like clinker rock formed when fires in coal outcrops burned back into hillsides and baked and melted the overlying sandstone and shale. Clinker outcrops cover 1600 square miles of the basin and represent natural burning of tens of billions of tons of coal. Isotopic ages of zircon grains in baked sandstones reveal that coal has burned to form clinker throughout the past few million years.

Additional Key Words: clinker, geochronology, geomorphology

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Introduction

Coal bed fires are not only found in abandoned and active mines. They are also natural events that have occurred over geologic time when coal beds were exposed by erosion. Hundreds of natural and mine-related coal bed fires are burning today in the Powder River Basin (PRB) of southeast Montana and northeast Wyoming – an area close to this year's NAAMLP conference in Billings, Montana. This article is a short overview of research conducted in the PRB over the past thirty years on the subject of coal bed fires, especially natural fires. The paper will discuss several "burning questions", using the PRB as an example of processes that occur in many geologic basins that contain coal:

- What starts coal bed fires?
- What types of coal bed fires occur today?
- What evidence shows that coal beds have burned in the past?
- How much coal has burned?
- Over what period have coal beds burned?
- What was the rate of natural burning?

Causes of Coal Bed Fires

What starts coal bed fires? Before any fire starts, conditions have to favor ignition. There must be fuel, air, and heat. First, fresh coal surfaces have to be exposed to air. Second, the coal bed has to be above the water table; i.e., not saturated. The natural process of erosion brings coal above the water table as coal beds are exposed by streams that carve down through the nearly flat-lying sedimentary strata of the PRB. Surface mining creates highwalls that expose fresh coal seams to air and drain out the groundwater, and subsidence of mined-out rooms between pillars in underground mines allows air to infiltrate. Once air is available, the heat produced by chemical reactions, range fires, or lightning strikes can trigger fires in coal beds. The high volatile subbituminous coal in the PRB is particularly prone to spontaneous combustion caused by oxidation and heat of wetting reactions (Lyman and Volkmer, 2001; Kim and Chaiken, 1993). Weathered coal outcrops are less likely to spontaneously combust, as the coal is already degassed and oxidized.

What extinguishes coal bed fires? The coal beds in the PRB are nearly horizontal, and when a natural fire starts it first spreads along the outcrop. With time, it burns deeper into the hillside, causing the overlying rocks to progressively subside into the burned-out void left by the loss of the coal. The resulting fracturing allows air to enter and gas to escape, letting the fire continue. The fire goes out naturally when the overburden becomes so thick that fractures from the collapse fail to reach the surface to draw in more air, when the fire burns down to the water table in the coal, or when surface runoff fills the fractures with sand, clay, or water and chokes off the fire.

Modern Coal Bed Fires

Types of Fires

What types of coal bed fires occur today? Coal bed fires are common in the coal basins of the American West. The explorers Lewis and Clark had many encounters with natural coal bed fires in their journeys along the Missouri and Yellowstone Rivers two centuries ago. They correctly noted the association of burning coal beds with the “burnt hills” of clinker in the northern Great Plains. Clark named the river we now call the Powder River the Redstone River, because of all the cobbles of reddish clinker in the riverbed (Thwaites, 1969). In the PRB, there are four main types of coal bed fires:

1. **Fires in abandoned underground mines –** These are most common in areas mined in the late 1800’s and early 1900’s before large scale surface mines became dominant, such as the underground mines along the Tongue River valley north of Sheridan, Wyoming. As the rooms between pillars collapse, sinkholes allow air to enter. Coal bed fires sporadically ignite in the sinkholes and occasionally produce explosions (Dunrud and Osterwald, 1980).
2. **Fires in highwalls and spoil piles at active surface mines –** Most surface mining occurs in a belt east of the towns of Gillette and Wright in northeast Wyoming, as well as in Montana in the Tongue River valley near Decker, and near Colstrip. Nearly 400 million tons are mined each year in the Wyoming portion of the PRB and about 40 million tons in the Montana portion. Many of the fires at surface mines occur in spring when the air is damp but the coal is dry. Surface mines in this region have regular programs to extinguish the many fires that start spontaneously in the exposed coal.
3. **Fires on natural coal outcrops –** Outcrops of fresh coal in gullies, streambanks, and highwalls of landslides are especially prone to combustion (Figure 1). In the semiarid climate of the PRB, wild range and forest fires triggered by lightning regularly ignite coal beds. Many of these fires appear to have been started by burning juniper and pine trees that were rooted in coal beds. Sixty coal bed fires were ignited by range fires north of Gillette in July of 2002 and reclaimed by the U.S. Bureau of Land Management, the Campbell County Fire Department, and surface owners during the following year (Heffern and Coates, 2004). Spontaneous combustion of fresh coal also causes fires.
4. **Low level smoldering of coal beds –** These are most apparent in winter when the temperature difference is greatest and may be revealed as bare patches of ground or ice-encrusted vents where the snow cover has melted. Rising steam or green vegetation in an otherwise snow covered area may also indicate smoldering.

Figure 1. Natural coal bed fire along bank of Tongue River north of Sheridan, Wyoming. Note concentric fissures created by collapse of coal bed.
Photo courtesy of Gerald Queen, BLM Buffalo Field Office.

Legal Authorities for Reclamation

In the western United States, two laws provide sources of funding to fight fires in coal beds.

1. The Surface Mining Control and Reclamation Act of 1977 (SMCRA) – P.L. 95-87 – can be used to reclaim coal fires related to past mining. Section 401(c)(1) of this Act authorizes "prevention, abatement and control of … burning coal" by the Department of Interior in areas "adversely affected by past coal mining". The Rural Abandoned Mine Program in Section 406 has also been used by the Department of Agriculture as a limited source of fire control funds. The law does not provide a specific cap on appropriations.

2. The Act of August 31, 1954 – P.L. 83-738 – covers control of natural coal outcrop fires as well as mine fires. However, under this law, appropriations nationwide are limited to $500,000 per year. On State or private land, projects funded under this law require 50% in matching funds.

Both of these laws are mainly administered by the Department of Interior's Office of Surface Mining (OSM) or its delegated State agencies. Other incentives, such as potential loss of valuable coal reserves, timber, or forage, may lead other Federal, State, and local agencies and governments, mine companies, and private landowners to control coal bed fires with or without financial help from these two laws.

Figure 2. Smoldering coal bed fire at old Canfield mine USBM reclamation project, Rochelle Hills, Wyoming.

In the Wyoming PRB, the State Department of Environmental Quality, Abandoned Mine Land Division, has taken action on six coal bed fires in Sheridan County and two in Campbell County, and is monitoring or observing six other fires. The now-disbanded US Bureau of Mines (USBM) conducted 39 fire control projects in the PRB between 1949 and 1977 – 22 in Wyoming and 17 in Montana (Kim and Chaiken, 1993). Success of these efforts has been limited, and some fires still smolder (Figure 2). Open fissures or noxious gases may pose health and safety problems. Fire control has proven to be very expensive and some fires are allowed to burn unless the public wants them out.

Ancient Coal Bed Fires

Evidence in the Rocks

What evidence shows that coal beds have burned in the past? Clinker – rock that has been baked, welded, or melted by the burning of underlying coal beds – provides a record of past coal-bed fires. Clinker, hardened by heating, forms resistant reddish layers that cap plateaus, hilltops, and escarpments in the landscape of the PRB. The clinker is highly fractured, which allows rainfall and snowmelt to infiltrate rather than run off the surface and erode the outcrop. The unbaked overlying and underlying rocks are eroded more rapidly, leaving the clinker standing in relief (Coates and Heffern, 2000). In the Rochelle Hills of eastern Wyoming, natural burning of the Wyodak-Anderson coal zone has left an eastward-facing escarpment 300 to 700 feet high, capped by a layer of reddish clinker 60 to 150 feet thick (Figure 3). Clinker fragments are abundant in landslides below these escarpments. It is, essentially, a landscape formed by fire.

Figure 3. Clinker escarpment, Keyton Canyon, Rochelle Hills, Wyoming.

Structure of Clinker

The block diagram in Figure 4 shows the structure of a typical clinker hillside. Note the progressive collapse of the sandstone and shale layers in the overburden as the coal bed fire advances back into the hillside. Towards the outcrop, coal thickness tapers to zero as increasingly lower parts of the coal bed are burned. As the burn front retreats from the outcrop, the overburden sags into the void left by the burned coal, leaving a chaotic mass of jumbled rocks. Slump blocks are separated by tension cracks filled with welded breccia and paralava that indicate areas of intense heating.   Rock types in the clinker reflect the rock types in the overburden, and have varying degrees of hardness depending on the degree of heating. Baked sandstone retains its grain structure but hardens to a brick-like texture, while baked shale layers may weld together to form a ceramic rock called porcellanite. Paralava forms where rocks were heated enough to melt. Chimneys of welded breccia and paralava are very hard and resistant to erosion and may stand up to 20 feet above the surrounding landscape. At the base of the clinker is a layer, up to a few feet thick, of light tan ash and glassy, greenish scoria, formed by uncombusted minerals left over from the original coal bed, which may have been tens of feet thick (Figure 5). As most of the heat of burning is conducted upward, strata more than a foot or two below the base of the original coal bed are unbaked (Coates and Heffern, 2000; Papp, 1998).

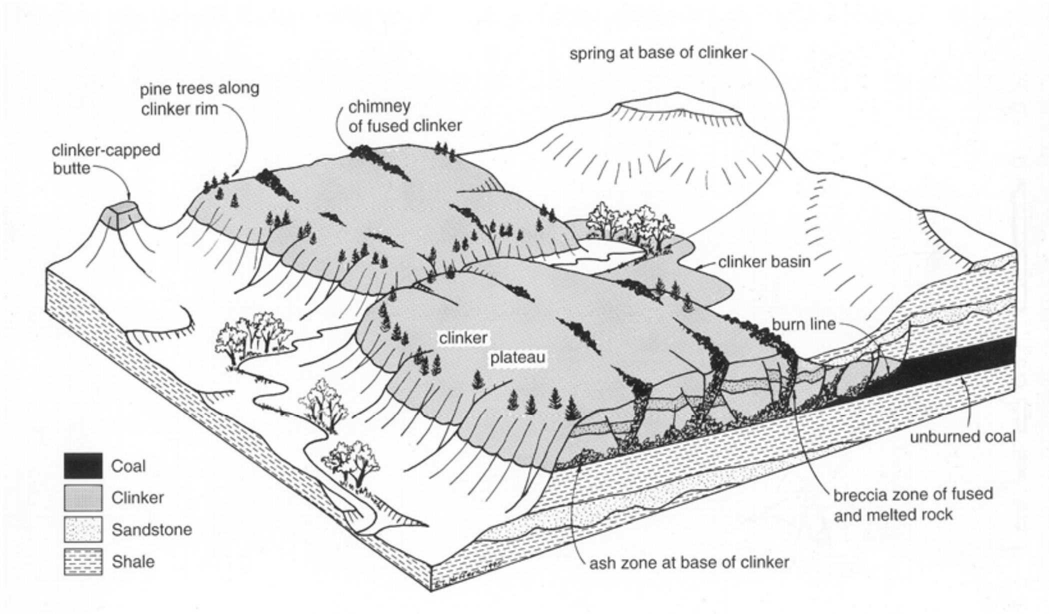

Figure 4. Block diagram of clinker landscape (from Heffern and Coates, 1997).

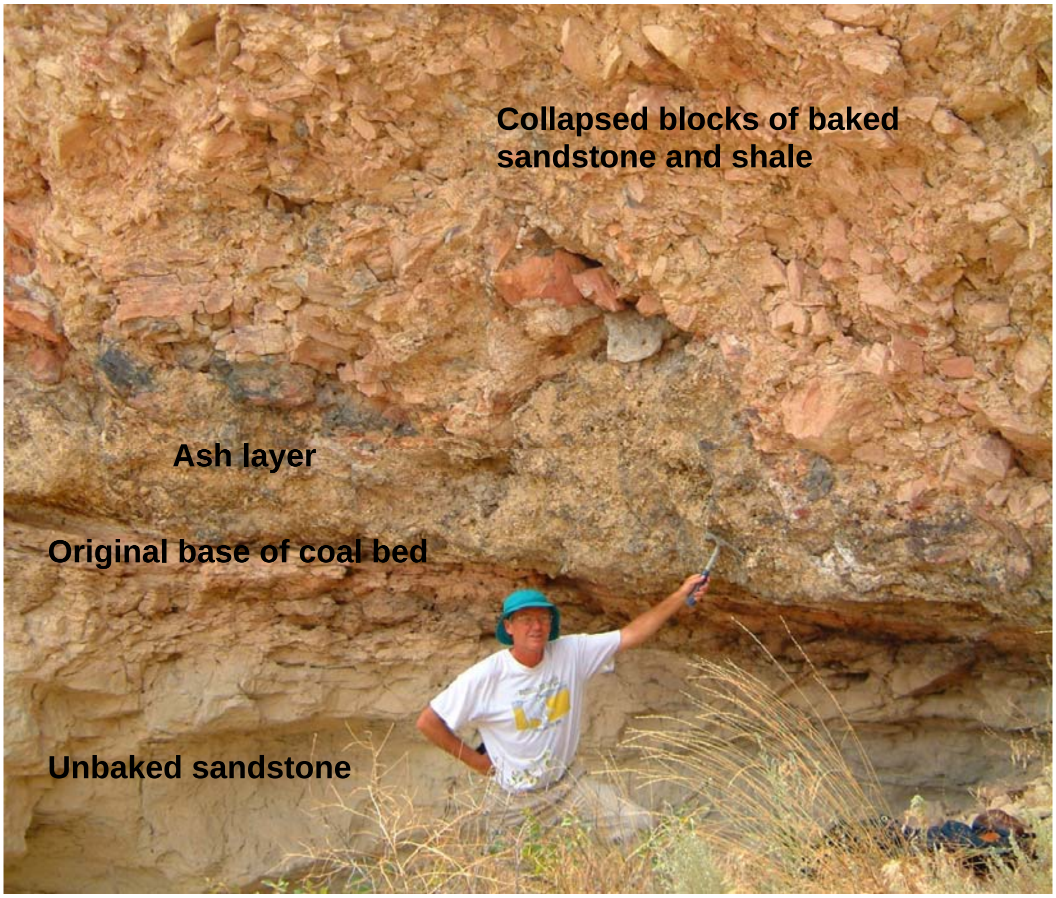

Figure 5. Clinker structure in cliff near Ashland, MT.

Extent of Clinker

How much coal has burned? Clinker outcrops cover 1600 square miles of the PRB – about 1100 square miles in Montana and 500 in Wyoming (Heffern et al., 1993; Heffern and Coates, 2004). The clinker averages 40 to 80 feet thick but can be as much as 200 feet thick. A review of geologic reports and mine plans and our experience in the field indicate that clinker in the PRB is commonly two to three times thicker than the underlying coal bed that burned. If we assume that the coal beds that burned to produce the clinker averaged 25 feet thick, then the clinker in place records the prehistoric burning of 47 billion tons of coal. This is a conservative estimate, as coal beds in places may be over 50 feet thick and the thicker coals have produced the most extensive sheets of clinker.

These clinker outcrops are only remnants of a much larger volume of clinker that has been removed by erosion. As erosion deepened and widened valleys, successively lower coal beds were exposed and burned back into the hillsides. Clinker fragments were carried downslope and downstream and are found in the alluvium and gravel terraces of the tributaries of the Missouri River that drain the PRB. The clinker remaining in its original position is probably an order of magnitude less than the volume of clinker produced over time, so the amount of coal burned by natural processes probably is closer to several hundred billion tons (Heffern and Coates, 2004).

Much of the clinker was formed by burning of three regionally extensive coal zones in the Tongue River Member of the Paleocene Fort Union Formation – the Wyodak-Anderson zone in both Montana and Wyoming and the Knobloch and Rosebud-Robinson zones in Montana (Heffern et al., 1993; Flores and Bader, 1999). In the overlying Eocene Wasatch Formation, mostly in Wyoming, extensive clinker was produced by the burning of the Lake DeSmet coal zone near Buffalo and Sheridan, as well as the Felix coal zone near Gillette and Wright. Lake DeSmet itself, north of Buffalo, fills a basin created by natural burning of a coal zone as much as 200 feet thick (Mapel, 1959).

Plate 1, at the end of this article, is an oversize map in Adobe Acrobat format (HeffernWYplate1.pdf) showing clinker and coal bed fires in the eastern PRB of Wyoming. The clinker of the Wyodak (Wyodak-Anderson) coal zone is just east of the 17 active and permitted mines on the eastern flank of the PRB (Figure 6), which produce from this coal zone west of the burn line. These mines produced 382 million tons in 2004 (Energy Information Administration, 2005) and have removed coal from an area of more than 80 square miles over their lifetimes. Plate 1 also shows the locations of several known active or historic coal bed fires. In the map area of Plate 1, clinker produced by prehistoric burning of coal beds covers 178 square miles (7 percent of the total map area); 161 square miles of this total comes from prehistoric burning of the Wyodak coal zone.

Figure 6. Clinker in foreground of North Antelope / Rochelle coal mine.

Age of Clinker

Methods of Dating

How does one determine the age of clinker? Clinker has been dated by three means: (1) uranium-thorium/helium ratios of detrital zircon grains in baked sandstones (ZHe ages); (2) fission-track counts of detrital zircon grains in baked sandstones (ZFT ages); and (3) paleomagnetic orientations of magnetite, hematite, and goethite in paralava (Heffern et al., in press). The first two methods – detrital thermochronometry (Reiners, 2005; Naeser, 1979) – provide absolute ages. When detrital zircons in the overlying sediments are baked, they are annealed, and ZHe and ZFT ages show the age of cooling. The only fission tracks or helium in the zircon grains formed after the coal bed burned to produce the baked sandstone. Because the uranium in the zircons is not abundant, fission tracks are sparse and ZFT dates have a large error. Recent work shows that ZHe dates have less error; while they confirm the fission-track ages in general, they are more precise. The third method provides relative age – if the magnetic orientation is reversed, the clinker burned before the last reversal at 0.78 million years ago (Jones et al., 1984).

Ages of Burning

Over what period have coal beds burned? The time during which coal has been burning in this region can be estimated using isotopic ages of clinker. ZHe and ZFT dates show that at least as far back as four million years (Ma) ago, and on through to the present, coal beds have been burning from natural causes in the PRB – not as a single large fire, but as many fires, large and small, separated in space and time.

A total of 26 ZHe and 38 ZFT ages have been derived by Peter Reiners of the University of Arizona and Charles Naeser of the U.S. Geological Survey for clinker samples from the PRB (Heffern et al., in press). During summer 2006, additional samples were collected for future ZHe analysis from 51 locations by Reiners, Catherine Riihimaki of Bryn Mawr College and students, and the author.

The oldest in-place clinker samples dated thus far, with ZFT ages of 2.9 and 2.2 Ma, come from the summits of the Little Wolf Mountains southwest of Colstrip, MT. This narrow, isolated range stands 1,100 feet above the surrounding landscape and is capped by a layer of clinker as much as 100 feet thick. All other dated ages of clinker outcrops are 1.5 Ma or younger.

However, a clinker boulder at the base of a 60-foot thick gravel deposit on a strath terrace 1200 feet above the present-day Yellowstone River, west of Colstrip, has a ZFT age of 3.8 Ma. This site is 1000 feet below and 14 miles north of the summits of the Little Wolf Mountains. This age shows that coal beds were being exposed and subjected to burning in Pliocene time (Heffern and Coates, 2004). Boulders of clinker were eroded from the outcrop and deposited as gravel in the valley of a large river. This gravel was later isolated as a terrace when the river cut down to a lower level. The new samples collected in the summer of 2006 include several additional clinker boulders from this location. We hope the new dates can better bracket the age of the gravel deposit.

Isotopic ages can also trace the history of burning in a local area. Plate 1 shows ZHe and ZFT ages of clinker outcrops at a number of locations in the Rochelle Hills east of the Jacobs Ranch, Black Thunder, and North Antelope / Rochelle coal mines. This large clinker escarpment (Figure 3) stands on the east side of the PRB. The oldest clinker, on the tip of the headland to the east, stands about 700 feet above local drainage and is more than one half million years old (Coates and Naeser, 1984). The Wyodak coal bed that formed the clinker dips 50 to 60 feet/mile towards the west, and the clinker ages decrease in that direction. Six miles to the west, where clinker meets unburned coal, a natural coal fire was extinguished in the mid-20th century (Russell and Smith, 1951), and coal mines extract shallow coal that has not burned (Figure 6).

Near Ashland, MT, a plateau capped by clinker over 100 feet thick, derived from ancient burning of the Wyodak-Anderson coal zone, forms the rim of the Tongue River valley. This plateau stands 1000 feet above the level of the clinker of the Knobloch coal zone, which forms a broad bench less than 300 feet above the present-day level of the Tongue River (Figure 7). Both coal zones dip to the south while the Tongue River flows north. The Knobloch zone intersects the Tongue River near Birney Day School, MT, while the Wyodak-Anderson

Figure 7. View of Tongue River valley, looking west towards the town of Ashland from U.S. Highway 212. The Wyodak-Anderson clinker forms divide on horizon; the Knobloch clinker forms broad bench near present river level.

zone intersects the Tongue River near the mines at Decker, MT, just north of the Wyoming border. No coal has burned below the present level of the river, which controls the water table. ZFT and ZHe clinker ages show that the Wyodak-Anderson coal was exposed over a million years ago by the prehistoric Tongue River, and burned progressively downdip to the south (Heffern et al., in press; Heffern and Coates, 2004). As the Tongue River cut down through the strata of the Fort Union Formation, successively lower coal beds were exposed and burned to produce clinker, while backwasting along side drainages exposed more of the Wyodak-Anderson coal farther away from the river. More recently (0.6 Ma or less), the Knobloch coal zone was exposed and burned downdip to produce broad benches of clinker near present river level.

Rates of Burning

What was the rate of natural burning? If we assume that the 1600 square miles of clinker in place represent burning of about 40 billion tons of coal over the past two million years, then an average of 20,000 tons of coal burned each year. However, the clinker in place may be an order of magnitude less than the clinker eroded away. A more likely estimate is that hundreds of thousands of tons of coal burn naturally each year. In historic times, this rate may be less because government agencies and ranchers have extinguished many coal bed fires.

Assuming complete combustion of the coal, 1.75 tons of CO_2 are produced from each ton of subbituminous coal burned from the PRB (Hong and Slatick, 1994). Although the rate of natural burning is much less than the current rate of coal mining, hundreds of billions of tons of CO_2 have been released into the atmosphere by natural coal fires in the PRB over the past few million years.

Conclusions

Over 400 million tons of coal are mined each year in the PRB. All this coal is produced by surface mining methods, which remove nearly all the coal and cover the mined area with waste rock, limiting access to air. Coal bed fires on highwalls or in mining pits are quickly extinguished. Consequently, uncontrolled coal fires from current mining are only a minor problem. This mining method is in contrast to underground mining methods, which remove only part of the coal and leave voids that can collapse and allow air to enter the mined area, making fires more likely. Most of the mine-related coal fires in the PRB are in abandoned underground room-and-pillar mines dating from the first half of the 20th century, where access to air has allowed fires to become established in old mine workings.

However, natural coal bed fires have occurred throughout the past several million years in the PRB and continue to burn tens to hundreds of thousands of tons of coal each year, triggered by range and forest fires, lightning strikes, and spontaneous combustion. The limited number of ZHe and ZFT ages derived to date from clinker can provide a glimpse at deciphering the geologic history of the basin over the past several million years, but are not adequate for detailed analysis of erosion rates. Some general patterns have become evident. We now know that coal beds have been exposed and have burned naturally since early Pliocene time. The oldest clinker preserved in place is the thick clinker capping the higher divides. Detrital clinker in gravel terraces can provide still older dates of burning. Laterally eroding clinker plateaus and sequences of clinker produced by stacked coal beds can provide horizontal and vertical erosion rates for specific areas.

The PRB is a giant natural laboratory for coal fire studies. Success in controlling coal bed fires is difficult, and only a temporary measure unless the coal behind the fire is mined out. Over geologic time, coal beds will continue to burn as they are exposed by regional erosion. Those who understand the geologic history of coal bed fires are better able to understand the limits of methods to control present-day coal bed fires.

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Clinker and Coal Bed Fires in the Eastern Powder River Basin, Wyoming

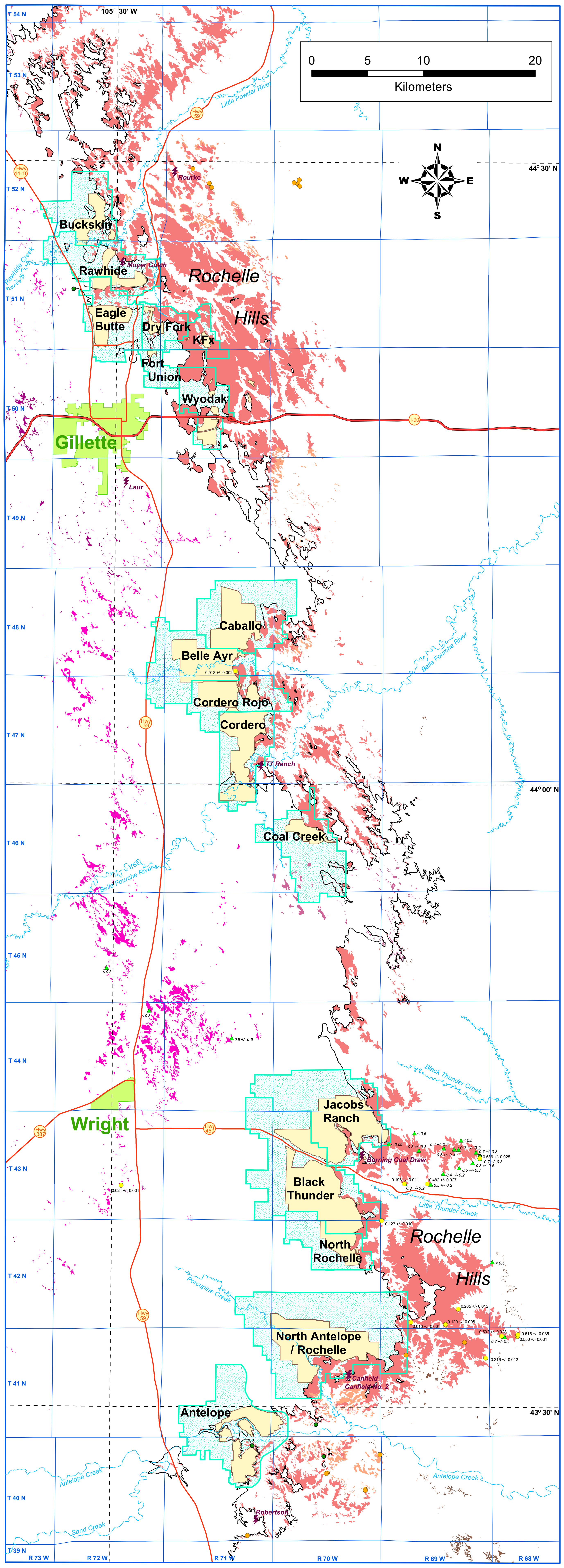

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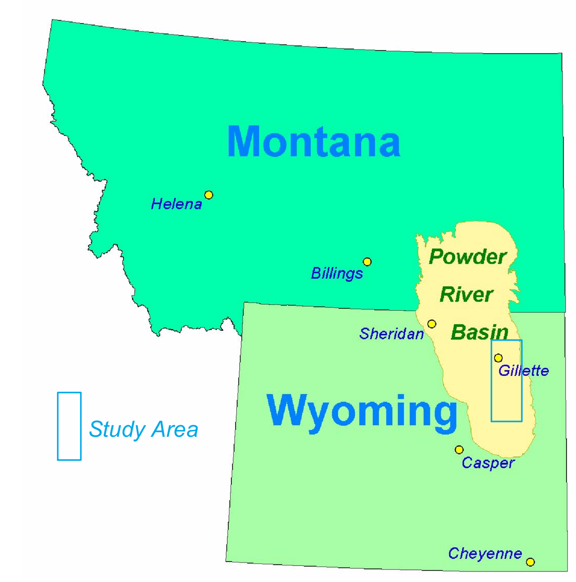
Plate 1
Modern and Ancient Coal Bed Fires
in the Powder River Basin

by E.L. Heffern, U.S. Bureau of Land Management, Cheyenne, WY



Coal Bed Fires

The Powder River Basin, with its dry climate, low-rank coal beds rich in volatile matter, and common range fires, provides ideal conditions for coal bed fires. Exposed coal beds above the water table have ignited due to causes as diverse as lightning strikes, wildfires burning trees and bushes rooted in coal beds, spontaneous combustion in coal mines and outcrops, and campfires lit on coal beds.

Selected historic and/or active coal bed fire

Name of fire	Size	Type of fire	Date of origin	Date of control project
Moyer Gulch	5 acres (2 hectares)	Mine fire	1885, set by horse thief?; burning 1915	1935, CCC; 1950, USBM
Little Thunder Basin (Burning Coal Draw)	360m x 180m; 20m deep	Outcrop fire	Burning since 1870's or earlier	1951, USBM
Laur	90m x 120m	Mine fire	Burning since 1939 or earlier	1939, CCC; 1950, USBM
Canfield and Canfield No. 2	340m x 180m; 30m deep	Mine fire	Burning since 1925	1950, USBM; 1964, USBM; still smoldering
Robertson	120m x 30m	Outcrop fire	Unknown; as long as locals recall	1964, USBM
Rourke	3 small fires	Outcrop fire	July 2002 range fire	2002, CCFD
T7 Ranch	Unknown	Outcrop fire	Burning since 1800's; visited in 1911	Unknown

CCC = Civilian Conservation Corps; USBM = U.S. Bureau of Mines; CCFD = Campbell County Fire Department

The above listed fires are only a small sample of known active or historic coal bed fires in the map area. For example, Goodson and Associates (1986), in a mine fire control study for the State of Wyoming Department of Environmental Quality, cited 41 known coal bed fires in Campbell County and 7 in Converse County. Kim and Chaiken (1993) listed 22 U.S. Bureau of Mines coal bed fire control projects in the Wyoming part of the Powder River Basin and 17 projects in the Montana part of the Basin between the years 1949 and 1977.

Clinker Outcrops

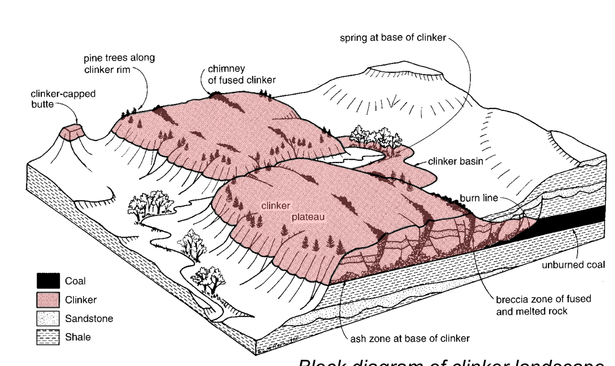
Clinker is rock that has been baked, welded, and/or melted by burning of underlying coal beds. Clinker forms reddish layers that cap hills and escarpments in the landscape. In this map, the Rochelle Hills form an east-facing escarpment capped by clinker of the Wyodak coal bed, which is being mined just west of the crop/burn line. The shade of clinker on this map is coded to natural burning of the following coal zones in the Eocene Wasatch and Paleocene Fort Union Formations, from highest to lowest stratigraphic level:

Name of Clinker / Coal Zone		Extent of Clinker in Area of Map (in square miles / square kilometers)
Lower Ulm		**1.1 / 2.8**
Felix		**13.9 / 36.0**
Upper Split	**Wyodak**	
Main Wyodak	**Wyodak**	**161.4 / 418.0**
Lower Split	**Wyodak**	
Pawnee		**1.3 / 3.4**
		Total 177.7 / 460.2

Additional clinker may be present in the subsurface, as much as a hundred meters beyond where it is exposed on the surface, as well as beneath younger alluvium. Clinker is also common in landslides and talus deposits below clinker-capped escarpments.

Full-seam crop line (burn line) of main Wyodak coal bed

Some coal may be present or may have been mined beyond the full seam line, where only the upper part of the coal bed was eroded or burned. The full seam crop lines of the Lower Ulm, Felix, Pawnee and other coal beds are not shown.



Block diagram of clinker landscape

Age of Clinker

How long ago did coal at a given location burn to form clinker? Clinker can be dated by several means, including uranium-thorium / helium ratios and fission-track counts of detrital zircon grains in baked sandstones, as well as paleomagnetic dating of magnetite, hematite, and goethite in paralava. These dates, in turn, help us to better understand how the landscape evolved over geologic time as major river systems cut down into the sediments of the Powder River Basin, and the rate at which coal beds were exposed, burned, and gases exhaled into the atmosphere.

Uranium-Thorium/Helium (ZHe) ages of clinker, in millions of years (Ma)

(analyses from Reiners, P.W., in Heffern, E.L., Reiners, P.W., Naeser, C.W., and Coates, D.A., (in press), Geochronology of clinker and implications for evolution of the Powder River Basin landscape, Wyoming and Montana: In Stracher, G.B. (Ed.), upcoming publication on Wild Coal Fires: Geological Society of America.
indicates location of additional samples collected in summer of 2006 for future analysis.)

Zircon fission-track (ZFT) ages of clinker, in millions of years (Ma)

(analyses from C.W. Naeser, in Heffern, E.L., Reiners, P.W., Naeser, C.W., and Coates, D.A., (in press), Geochronology of clinker and implications for evolution of the Powder River Basin landscape, Wyoming and Montana: In Stracher, G.B. (Ed.), upcoming publication on Wild Coal Fires: Geological Society of America. Data modified from dates in Coates, D.A., and Naeser, C.W., 1984, Map showing fission-track ages of clinker in the Rochelle Hills, southern Campbell and Weston Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1462.)

Paleomagnetic samples of clinker (all with normal polarity)

(from Jones, A.H., Geissman, J.W., and Coates, D.A., 1984. Clinker deposits, Powder River Basin, Wyoming and Montana: a new source of high-fidelity paleomagnetic data for the Quaternary. Geophysical Research Letters, 11 (12): 1231-1234. American Geophysical Union. The normal polarity indicates the coal burned more recently than the Matuyama-Brunhes magnetic reversal at about 0.78 Ma.)

Coal Mine Data

Mined areas through 2004

The coal mines in the eastern Powder River Basin are the largest in North America and produce over 400 million short tons per year. Areas where coal has been removed are approximate, and are based on mine plans and annual reports of coal mine permits on file with the Wyoming Department of Environmental Quality, Land Quality Division. Total mined areas cover about 80 square miles (208 square kilometers). Each mine has a program to quickly extinguish coal bed fires in mining pits, highwalls and spoil piles.

Coal mine permit boundaries as of 2004

(from Wyoming Department of Environmental Quality, Land Quality Division (DEQ/LQD). Boundaries are approximate and do not include narrow rail and road corridors. Adjacent mines have overlapping permit boundaries due to factors such as overstripping. In overlap areas, permit boundaries for this map were drawn along boundaries of coal leases controlled by each mine. For current and exact boundaries, please examine the permit maps for each mine on file at DEQ/LQD.)

Other Legend Data

Cities — **Interstate highways**

Township boundaries — **Major paved roads**

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